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Emerging Technologies for Hydrologic and Water Quality Modeling Research

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Abstract. *During the past two decades there has been a dramatic increase in the development and application of hydrologic and water quality models to evaluate complex environmental processes and to assess nonpoint source pollution of soil and water resources. Recognizing that advancements in modeling continue to be driven by developments in computer technology, it is worthwhile to examine some of the current and emerging computer technologies that hold great promise for advancing the use of hydrologic and water quality models. An attempt is made to forecast and briefly discuss the impact that technologies such as geographic information systems, global positioning systems, and scientific visualization will have on the future of hydrologic and water quality modeling. Forecasting is a very risky business, not because of our chronic inability to predict what will happen in the future but also because such speculation raises questions about what we modelers and model users desire and value. The thesis of this article is that some current and most of the emerging technologies will facilitate development and widespread use of hydrologic and water quality models for water resources management and decision making in the future.* ***Keywords.*** *Modeling, Geographic information systems, Expert systems, Remote sensing, Global positioning systems, Visualization.*

Improved understanding of processes that influence water flow and contaminant transport in the terrestrial environment has yielded a spectrum of mathematical models. These models (1) provide the framework for integrating knowledge about various parts of the physical system to achieve a coherent view of the whole system, (2) codify knowledge about processes occurring within the physical environment into logical sets of equations, (3) provide the tools for reliable and quantitative assessment of complex environmental processes over space and time, (4) identify strengths and weaknesses in scientific knowledge which can be used to direct future research, and (5) facilitate the analysis of what if scenarios and the extrapolation of their results across landscapes and management (Office of Technological Assessment, 1982). The need to model hydrology and water quality has become more critical as the scientific community assesses the effects of human activities on various ecosystems.

For the most part, existing hydrologic and water quality (H/WQ) models are useful for the purposes intended. These models are well regarded by their users and their developers have provided users with a wide range of analytical tools to evaluate the impact of human activities on water quantity and quality. The conscientious user can use these models to perform some credible analysis and make technically sound decisions. However, many of these models are complex and may suffer from such limitations as: (1) hyper-comprehensive – the model developers attempt to create comprehensive programs and computer codes capable of handling a wide range of applications; 2) data hungry – the model requires large volumes of input data that are often difficult to acquire and manage; 3) gross – in an attempt to maintain tractability, the sophistication of the model is often compromised; 4) complicated – the model contains excruciating details that the user loses control of the modeling process; and 5) expensive – extensive time and capital resources are required to develop the model, gather pertinent input parameters, understand how the model works, and conduct simulation experiments (Lee, 1973). Generally, some users of H/WQ models have described them as too expensive to operate and too complicated to understand. Some of these problems can be eliminated or minimized by making use of emerging technologies to improve the functionality and applicability of models in order to better serve the user community.

The scientific literature over the past several decades contain a large number of review articles detailing developments in and applications of H/WQ models (Rose et al., 1990; Leavesley et al., 1990; O'Connell, 1991). For example, Burge (1986) and Dodge (1988) review the trends and directions in hydrological science and hydrologic modeling. Dodson (1988) presented an overview of advances in computational technology and their relevance to hydrologic modeling research. Because of these previous reviews, this article will not provide any additional review of H/WQ models, but it will examine the impact emerging technologies may have on H/WQ modeling research. The primary focus of this article is on those computer-based technologies that hold exciting prospects and great promise for the future of H/WQ modeling.

During the past two decades, our insight into the impact of human activities on hydrology and water quality have been enhanced by applying a variety of computer simulation models. As background, a brief and general

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overview of the philosophy of modeling to facilitate classification of H/WQ models is presented. This overview is followed by an examination and discussion of several emerging technologies that might influence H/WQ modeling research. Some of the technologies examined include geographic information systems, knowledge-based systems, scientific visualization, software engineering, and remote sensing. The impacts on H/WQ modeling from other computer-based technologies for human-computer interaction are also examined. For each emerging technology, future research needs and opportunities in the field of H/WQ modeling are identified.

GENERAL PHILOSOPHY OF MODELING

Every attempt by humankind to understand and manage the environment has involved the use of models. In general, models can be defined (Batchelor, 1994) as "a deliberately simplified construct of nature erected for the purpose of understanding a phenomenon." Models can also be described as a simplified, hypothetical nature or reality. Therefore, in the broadest sense, models are metaphors for reality. They constitute a remarkably powerful tool for us to improve our understanding of environmental processes in unprecedented ways. Models offer a convenient and cost advantageous means of obtaining information on reality.

Since the time of Isaac Newton, great progress in understanding nature has been accomplished and a treasure-trove of models have been built. To appreciate the general types of models applicable to environmental management requires that these models be classified according to useful criteria. According to Woolhiser and Brakensiek (1972), models can be generally classified as material or abstract (fig. 1). A material (or physical) model represents a physical system that is assumed to be significantly simpler than the idealized system and is also assumed to have properties similar to the idealized system. Material models can be further classified as iconic, analog, or scaled models, depending on the idealization of the processes occurring within the physical system. Abstract models are symbolic and quite often are mathematical representations of the idealized physical system that has the important structural properties of the real physical system. These models are based either on an empirical or theoretical treatment of processes and mechanisms that influence the real physical system. While empirical models omit physical laws that relate to system processes and use the observed data to formulate system relationships, theoretical models use physical laws to develop a set of algorithms for the idealized physical system.

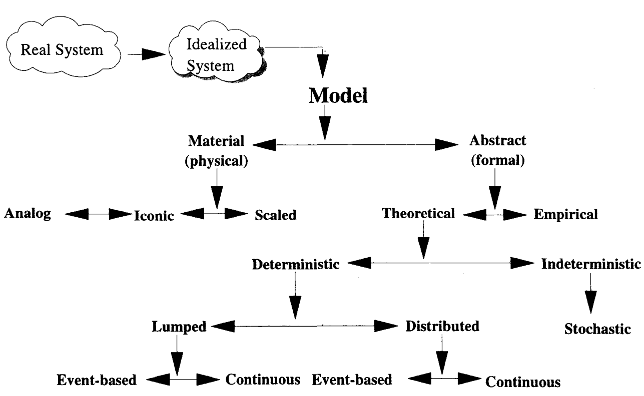

Figure 1–Simplified classification of models (adapted from Chow et al., 1988).

Following the classical review of models by Chow (1972) and Chow et al. (1988), one can further divide theoretical models into indeterministic and deterministic models. Indeterministic models, expressed either in probabilistic or stochastic terms, define the physical system such that they presuppose the outcome to be uncertain and random. Stochastic models, therefore, have some components that are random with a probability through space and time domain, and their outputs can be expressed in terms of a mean and a probability range. Deterministic models, on the other hand, ignore the impact of random perturbations on system parameters and define the physical system in such a way that the occurrence of a given set of events leads to an unequal-identifiable outcome. Under the deterministic modeling philosophy, only one set of output can be obtained from an equivalent set of input.

Deterministic models can be further subdivided into lumped or distributed models, depending on the treatment of space. A lumped, deterministic model represents the physical system as spatially homogeneous units and neglects the spatial variability of inputs within the system. Distributed models, on the other hand, assume that the physical system is made of uniform and discrete subunits, each characterized by a homogeneous set of input parameters.

Both lumped and distributed models can be further classified as continuous or event-based depending on the treatment of time. For example, an event-based lumped model simulates the response of the physical system to a single input (e.g., precipitation) and assumes that both the input and output parameters are time and space invariant. Continuous lumped models, on the other hand, sequentially simulate processes within the physical system on a time interval that can range from a fraction of an hour to a day (or even greater) and provide time series of model outputs. Table 1 shows a number of H/WQ models that fit the above classifications. The number and diversity of these models preclude either their comparison or discussion. Interested readers are referred to several recent reviews (Novotny and Olem, 1993; Ghadiri and Rose, 1992).

EMERGING TECHNOLOGIES FOR H/WQ MODELING

During the past decade, modeling of surface and subsurface hydrology and water quality has become increasingly popular and computational, primarily because of the widespread availability of digital computers with sufficient speed and storage capacity. For example, models developed originally for mainframes and large computer systems have been successfully and efficiently implemented on desktop computers. Moreover, new generation programming languages such as C and programming techniques such as object-orientation are now available for modeling. This section explores some of the technologies that hold exciting prospects for H/WQ modeling.

Table 1. Classification of theoretical models of hydrology and water quality

Model Acronym	Space Domain: Lumped	Space Domain: Distributed	Time Domain: Continuous	Time Domain: Event-based	Potential for Integration with GIS
ACTMO	X		X		Low
AGNPS		X	X	X	High
ANSWERS		X		X	High
ARM II	X		X		Very low
CNS	X		X		Very low
CPM	X		X		Very low
CPS	X		X		Very low
CREAMS	X		X		Low
EPIC	X		X	X	Low
FESHM		X	X	X	High
GAMES		X		X	Moderate
GLEAMS	X		X		Low
HSPF	X	X	X		High
LEACHM	X		X	X	Moderate
NPS	X		X		Very low
NTRM	X		X		Low
NLEAP	X		X		High
OPUS	X		X		Low
PLIERS	X		X	X	Low
PRMS	X		.X		High
PRZMII	X		X		Low
ROTO	X		X		Moderate
RUSLE	X			X	High
RZWQM	X		X		Low
SHE		X	X	X	High
SPAW	X		X		Low
SPUR	X		X		Moderate
STORM	X		X		Moderate
SWAT		X	X		High
SWM	X		X		Low
SWMM	X		X		Low
SWRRB	X		X	X	Moderate
TOPMODEL		X	X	X	High
USDAHL	X		X	X	Low
WEPP	X	X	X	X	Moderate

* Very low to high potential depends upon the structure of the model and the degree of difficulty that may be encountered in the process of linking the model with GIS. [Note: Very low to low potential to loose coupling of model and GIS; moderate potential corresponds to close coupling of model and GIS; high potential corresponds to tight coupling of model and GIS.]

Data Management Technology

For about a decade, the concepts of data management, offered by geographic information systems (GIS), have heralded a new era for H/WQ modeling. First, GIS technology allows modelers to acquire, organize, analyze, and display model input and output data in ways that were not previously possible (Burrough, 1986). Second, modelers can examine different scales of information and integrate data from a number of different sources including maps and tables. Finally, the flexible design of GIS provides the tools to analyze large-scale hydrologic processes and to evaluate the impact of changes in land management on water quality. Generally, GIS enables modelers to interactively examine what if relationships and to evaluate the impact of alternative management strategies (Burrough, 1989).

Numerous studies have described the use of GIS in H/WQ modeling (Fedra, 1993; Tim et al., 1992a; Chou and Ding, 1992; Zhang et al., 1990; Maidment, 1993; Frederickson, 1993; Goodchild et al., 1993; Kovar and Nachtnebel, 1993; Harlin and Lanfear, 1993). Generally, the use of GIS in H/WQ modeling has followed three basic coupling strategies summarized in figure 2. The first strategy shown in figure 2a involves the use of GIS to generate and organize input data and to display the output from models. In this strategy, generally referred to as loose coupling, data are passed from GIS to the model by editing and reformatting the data generated by GIS. A program editor or a simple interface program is used to convert data files in the ASCII or binary format from GIS to the model. In the same manner, the interface program converts model outputs to GIS for analysis and display. The second strategy, referred to as close coupling, involves slight modification of the operations in GIS software to provide a reasonably seamless linkage with the model. In this strategy (fig. 2b), extensive use is made of macros, macro languages, user-callable routines, and analytical functions in either GIS or the model. The third strategy, called tight coupling, is based on adding the functionality of GIS to the model and thereby avoiding data transfer between software packages or use of interface programs. Each coupling strategy provides numerous opportunities to enhance modeling and also has several limitations. These opportunities and limitations have been discussed in detail elsewhere (Tim, 1995; Burrough, 1995).

Progress has been made in coupling GIS with H/WQ models on the basis of either the loose or close coupling strategy discussed above. Vieux (1991) described the coupling of a distributed hydrologic model with ARC/INFO GIS to evaluate overland flow and nonpoint source pollution in agricultural watersheds. Tim and Jolly (1994) described the close coupling of the AGNPS model (Young et al., 1989) with the ARC/INFO GIS to evaluate nonpoint source pollution in a watershed. Tim et al. (1992a) discussed the tight coupling of the Virginia Geographic Information System (VirGIS) with simplified pollutant yield models to examine pollutant loading in an agricultural watershed. Srinivasan and Arnold (1994) described the tight coupling of the Soil Water Analysis Tool (SWAT) with GRASS GIS to facilitate basin-scale analysis of water quality. Several other researchers have discussed the use of GIS in hydrologic and water quality modeling (Hession and Shanholtz, 1988; DeBarry, 1991; Tim et al., 1992b; Srinivasan and Engel, 1994). In all of these studies the potential and the benefit of GIS in H/WQ modeling was clearly demonstrated. Presently, the use of GIS in H/WQ modeling research is beginning to reach a stage where users are maturing, and the strategies of coupling GIS with H/WQ models have been standardized.

In the future, modelers who use GIS to generate and organize input data can expect to see increasingly powerful computer processors as refinements are made in parallel processing and reduced instruction set computing (RISC) architecture. The integration of disparate databases and relational database management systems with GIS will provide flexible modeling environments. More dynamic analytical tools within existing GIS software are being developed, and commercial vendors are introducing raster-based modeling capabilities into traditional vector-based GIS programs. In the ARC/INFO GIS software, hydrologic and groundwater modeling functions (e.g., DARCYFLOW, POROUSPUFF, PARTICLETRACK) have been developed and included in the GRID module of version 7.0. Researchers are developing dynamic modeling command languages and toolkits, which will eventually find their way into many commercial GIS products. New and

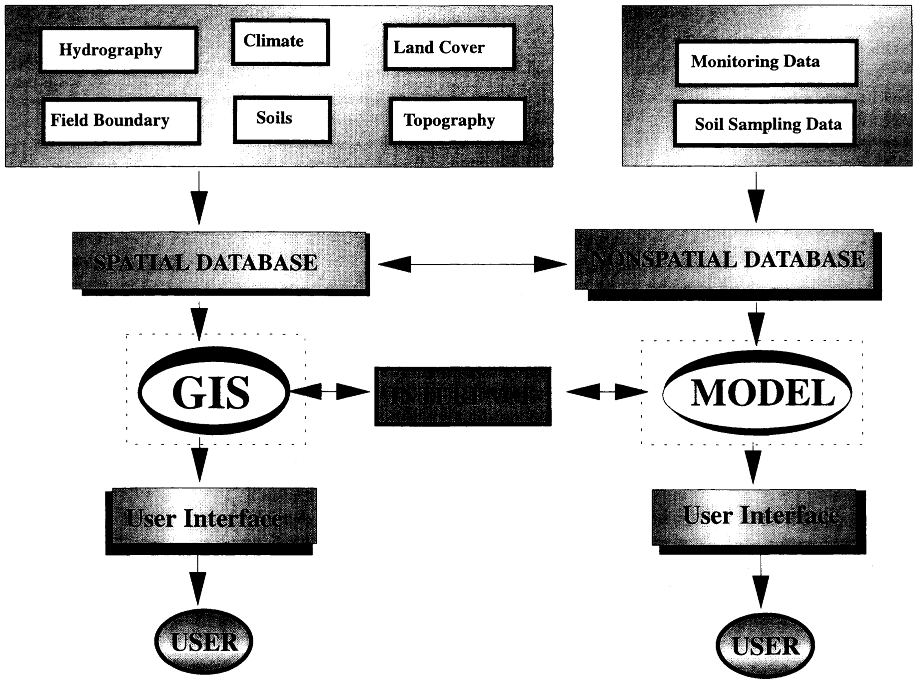

Figure 2–(a) Schematics for loose coupling of model and GIS.

exciting spatial data concepts including object-oriented databases and object abstraction will eventually find their way into GIS software packages. Finally, the development of fifth generation languages using less structured syntax will be a favorable addition to GIS. This will expedite development of seamless linkages between H/WQ models and GIS.

The widespread enthusiasm for GIS is undoubtedly justified by the potential attractiveness of the basic toolbox and the improved state-of-the-art technology to generate, organize, manage, interpret, and visualize model input and output data. However, potential problems and major limitations exist in the GIS technology, such that modelers are finding its use restricted to database management and data display. For example, most GIS software packages lack the appropriate data structure to handle interactions in H/WQ models. The solution of many H/WQ models requires matrix algebra, iterative procedures, and the mathematical techniques which are not part of the standard GIS toolbox and usually cannot be constructed by use of a macro language. Other limitations include the following: (1) nonspatial relationships in most H/WQ models are too complex to be modeled within GIS, (2) current GIS software packages are limited by their inability to fully incorporate time, and (3) basic data structures underlying models are rather primitive when compared to GIS data

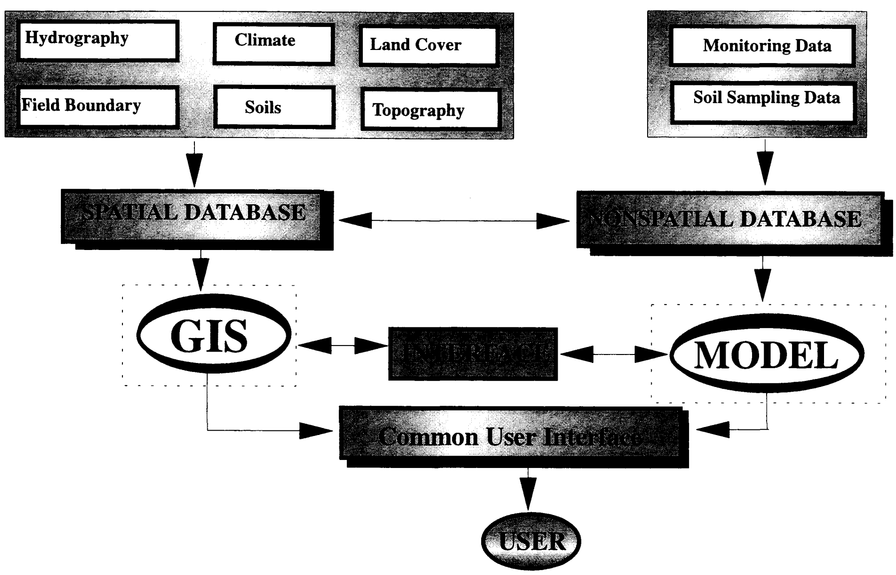

Figure 2–(b) Schematics for close coupling of model and GIS.

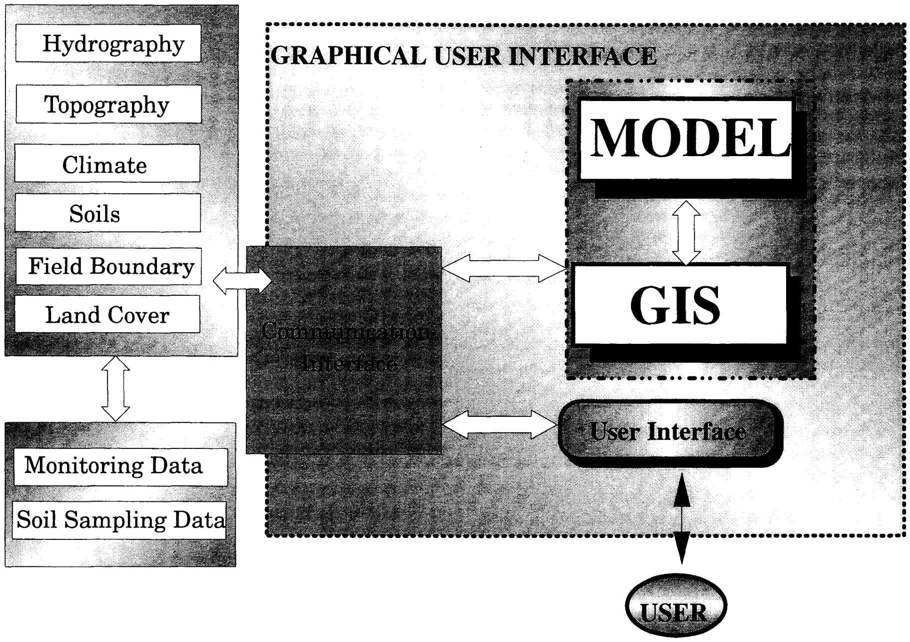

Figure 2–(c) Schematics for tight coupling of model and GIS.

structure. Despite these limitations, the future of GIS in H/WQ modeling is bright.

Technology for Human-computer Interactions

The effectiveness of a modeling system depends upon how accessible the information is to the user. In H/WQ modeling, most users may not be interested in the hardware component or the intricacies of the modeling system, but may simply be using the model to obtain a particular result with as little difficulty and confusion as possible. However, as the need to incorporate relevant processes into H/WQ model increases and the modeling systems become more complex and elaborate, novice users may become "lost" and unable to navigate the modeling system. Such a problem can significantly reduce the usability and desirability of a model and may be particularly daunting for an inexperienced user. Even experienced users can fail to exploit the full potentials of the model because they are unable to effectively navigate the modeling system, and hence, limit themselves to a set of familiar procedures. Recent developments in computer-based technologies for human-computer interaction provide a set of processes, dialogues, and actions through which users can interact with the hardware and software components of a modeling system. In this section, the techniques of human-computer interaction are examined and their relevance to H/WQ modeling are discussed.

Traditional User Interface. The evolution towards a more user friendly modeling environment began in the early 1970s with the development of user interfaces that enable modelers to edit input data and run models with only limited knowledge of the underlying computer hardware and software. These user interfaces were based on either a command-line, full-screen, or spreadsheet interface. The command-line interface, which is quite common in many H/WQ models, enables users to prepare and submit a single line of data to the modeling system. This mode of human-computer interaction can take the form of line by line entry of input data or specification of input data files. When the appropriate data or data files are specified, the user then waits for the modeling system to respond with the output or a listing of error messages. Typical examples of H/WQ models that adopt a command-line interface include GLEAMS (Leonard et al., 1987) and RZWQM (USDA-Agricultural Research Service, 1992).

In full-screen interface, users can view and interactively modify the input data or the problem configuration on the computer screen. The full-screen interface is much more flexible than the command-line interface since the computing environment can be structured to prompt the user for specific inputs and selection of modeling options. In addition, pop-up or pull-down menus are often used to facilitate user interaction with the different components of the modeling system. The full-screen interface has been adopted in a number of models, including NLEAP (Shaffer, 1991) and PRMS (Leavesley et al., 1990).

The spreadsheet interface, similar to the full-screen interface, is designed specifically to facilitate interactive entry, analysis, and display of input data on the computer screen. In the spreadsheet interface, a series of horizontal pull-down or pop-up menus facilitate data entry and data processing operations. The user can interact with the modeling system by editing the input data, performing error checks and simulation runs, and structuring the model output data files. The spreadsheet interface is usually enhanced by the use of pull-down menus which contain the modeling options. The AGNPS model is a typical example of a H/WQ model that adopts the spreadsheet user interface.

Graphical User Interface. With the interactive graphics limitations of traditional user interfaces, graphical user interfaces (GUIs) based on Windows-Icons-Mice-Pointers (WIMP) interface are needed. A major objective of GUIs is to present the modeling environment as transparent as possible to the user. Generally, GUIs promote interactive visual programming by using dataflow diagrams. A network editor enables the user to build applications by selecting data and techniques, both represented in iconic form, and connecting their input and output ports. Furthermore, GUIs improve the resilience, portability, modularity, configurability, and responsiveness of the modeling system (Sutcliffe, 1989).

Graphical user interfaces rely on pointing devices such as a mouse, icons, and pull-down command menus to facilitate user navigation of and interaction with the modeling system and to capitalize on the powerful visual processing capability inherent in human perception (Grudin, 1989). The use of the WIMP interface is intended to improve the "look and feel" of the modeling environment, making it more intuitive to use. Typical examples of GUIs include Apple Macintosh interface, IBM OS/2™, Open Look™, Microsoft Windows™, and OSF/Motif™ on X-Windows.

Innovations in human-computer interaction have resulted in the development of GUIs and other similar front-ends for H/WQ modeling. Fedra (1993) described the development of a GUI that facilitates the use of water resource models for planning and management. Roberts and Thurman (1993) described the structure of a GUI for accessing rainfall-runoff data on CD-ROM at the Agricultural Research Service's Water Data Center in Beltsville, Maryland. Brewer (1993) described a GUI that incorporates surface hydrologic modeling and an INGRES™ relational database management system to form a simulation modeling support system for river basin management. Here, the user interface was developed by using X-Windows. Liao and Tim (1994) described an interactive watershed water quality modeling system within a GIS environment. A GUI developed using XWindows and OSF/Motif™ facilitates user navigation of the model system, selection and execution of modeling options, and visualization of both basic and derived model data.

The user interface problem as it relates to H/WQ modeling is that users who wish to gain access to the components of and algorithms in the model are often frustrated by the complex interaction procedures. This sense of frustration often leads to misuse, under utilization, or outright unwillingness to use the model. Clearly improvements must be made in this research area to realize the full potentials of H/WQ models. As research in human-computer interaction expands, more generic GUIs will be developed to enhance H/WQ modeling.

Speech-recognition Interface. Speech interfaces as a form of human-computer interaction is relatively new, and the technology for speech recognition is currently being developed. Speech input has an intuitive appeal for a variety of reasons. For example, speech interfaces are relatively faster and more efficient than other modes of human-computer interaction; and in multitasking situations, speech inputs provide an additional response channel over which the workload can be spread. Generally, the advantage of speech interfaces is that they allow much faster data entry and are more natural to use.

Several advantages of speech interface have been recognized in simulation modeling. A speech interface can enhance user-computer interaction during the modeling process. For models that require keyboard entry of large amounts of data, speech interfaces may be faster especially for users who have never learned to type effectively. However, the future use of speech input in simulation modeling suffers from a number of problems: (1) currently the application of speech input is limited to highly specialized and highly-constrained tasks, (2) speech recognizers are subject to interference from background noise that may result in error in the data, and (3) even if the speech was recognized and the correct input data was provided, the natural form of language used by people is very difficult for the computer to interpret. A perfect speech recognition interface for modeling would be one that understands natural speech (fig. 3) to such an extent that it could not only distinguish differences in pronunciation, but also have the "intelligence" to resolve any conflicts in data ranges. Until some of these issues are resolved, progress in the use of speech-recognition interface as an efficient mode of human-computer interaction is likely to be slow. On the horizon, many

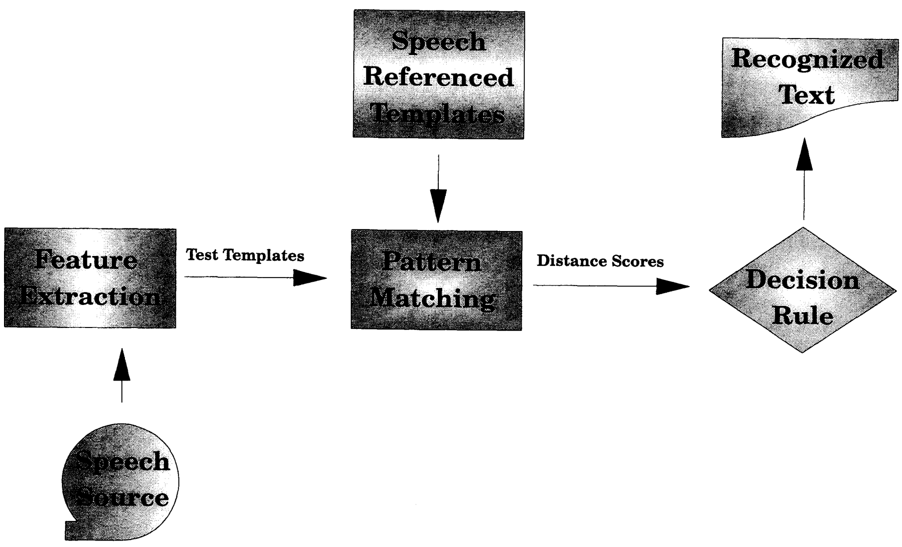

Figure 3–Traditional pattern recognition for speech recognition.

anticipate that a vocal interface will constitute a major turning point in the development of speech interfaces for human-computer interaction. In the interim, the technology for reliable voice recognition is still under development, and we can only speculate on its application in H/WQ modeling.

Scientific Visualization

The recent developments in computer hardware and software to cope with sophisticated graphical analysis of input and output data have led to the emergence of scientific visualization. Powerful computers are now able to provide image manipulation tools that encompass both real-time visualization of model outputs and virtual displays. Current applications of scientific visualization include medicine, chemistry, architecture, seismology, climatology, and meteorology. In these application areas, scientific visualization enables objects to be viewed from all external perspectives and to invoke insight into data through manipulable visual representations. Interest in scientific visualization can be traced to two- or three-dimensional plotting of data. In H/WQ modeling, scientific visualization can be used to display and animate sequences of model output images across time and space, allowing users to interact effectively with the database, to determine which parameters to display, and to provide multiple views of the data. In the past few years, scientific visualization has been developed primarily to help scientists extract ideas from large volumes of multidimensional data. The emphasis on ideation is at the exploratory end of this purpose continuum. A brief overview of two techniques for exploring data in visual form (e.g., animation) and for experiencing virtual worlds using all the human sensory channels (e.g., virtual reality) is presented.

Animation. An area of scientific visualization that is gaining acceptance and popularity within the scientific community is animation. Animation has been extensively used in the fields of communications and education, where there are well-developed protocols for creating animated images. Such images are commonly integrated with videos as in full-length feature films and television commercials. Animation provides useful creative ways of handling vague questions such as: What is going on? Is there anything interesting? What is happening where and when? Are there any discernible patterns?

In the field of H/WQ modeling, the use of animation is still at the research stages. Potentially, animated images can be used to describe landscape processes and to present the results of simulation modeling in real time. For example, sequence of images showing the effects of runoff events can be traced from the source area to the endpoint by draping model results onto a digital terrain model of the landscape. Animation can also (1) allow hydrologists to understand complex processes and to communicate computer-simulated events for management to make decisions, (2) enhance the many traditional phases of H/WQ modeling from initial debugging of the computer code to presentation of simulation results, and (3) facilitate isolation and removal of errors in the computer code and examine underlying control logic in models. Unquestionably, the greatest contribution of animation to H/WQ modeling involves the presentation of results either in real time or as snapshots. Through dynamic movement of color, animation can portray the intricacies of the modeling system in ways that were never realized by static graphics often limited to two-dimensional plots. As Smith and Platt (1987) noted, "animation makes likely and accessible what would otherwise be a dry and somewhat obscure presentation of tables and figures." However, the tools for and process of creating animated images in H/WQ modeling is currently very expensive.

Virtual Reality. Virtual reality is another area of scientific visualization which is currently being developed. The virtual reality technology uses computer images projected onto small screens within a headset and integrated pointing devices for simulating touch and sound. Hand movements in front of the face are seen on the computer screen, turning the head changes the screen display, and touching objects in the computer model leads to touch simulations. The virtual reality technology also generates photo-realistic images and permits users to interact directly with the computer representation of the virtual environment, using a fuller range of senses and faculties to do so. In H/WQ modeling, if the virtual environment were replaced with a virtual landscape and animated processes of surface or subsurface hydrology, one could recreate real-world situations and examine the impact of human activities. However, the major limitations of incorporating virtual reality into H/WQ models include the cost of the virtual reality technology, quality of the modeling database, structure of the model, and the ability of users to interpret virtual information presented. To fully incorporate the virtual reality technology in H/WQ modeling, a considerable effort must be focused on research and development. In addition, developing techniques to integrate senses of touch within a modeling system are needed.

Technology for Knowledge Engineering

A technology that has gained widespread acceptance within the H/WQ modeling community during the past decade is expert systems (ES) or knowledge-based systems (KBS). Although some distinctions have been made between ES and KBS in the literature, these terms have been used interchangeably to denote that branch of artificial intelligence that uses a heuristic representation of human expertise in a specialty domain to perform functions similar to those normally performed by a human expert in that domain (Buchanan, 1986; Barr et al., 1990). Generally, KBS function by encoding the decision-making abilities of an expert into a computer program in such a way that through an interactive process between the user and the program, solutions to ill-structured and ill-posed problems can be obtained. As pointed out by Denning (1986), KBS are designed to simulate the problem-solving behavior of a human who is an expert in a specialized area. Human expertise that is encoded into KBS includes experience, judgment, and problem-solving capabilities that have been acquired through numerous years of training and professional experience.

Knowledge-based systems differ from conventional computer programs since knowledge, which is usually represented in the form of rules, is treated separately from the problem-solving mechanisms called the inference engine (Barr et al., 1990). In KBS, three organizational structures are typically used to represent knowledge:

production rules, semantic nets, and frames. Production rules consist of "IF-THEN" logical decisions, where the "IF" represents the premise or condition and "THEN" qualifies the action or consequence. The linking of the "IF THEN" rules forms a rule- or knowledge-based reasoning strategy that can be used either as a diagnostic tool or as an interpretive tool. Semantic nets (or semantic networks) are used to represent nonrule-based or declarative knowledge according to an association among objects, events, or concepts where data are associated. Frames are used to group or categorize nonrule-based knowledge that is characterized by a number of attributes or related parameters and typically take the form of multiple databases in which all knowledge about particular objects or events are stored together. The main advantage of semantic nets over knowledge representation by production rules is that for each object or event, all relevant information is collected together to facilitate efficient access and manipulation.

Before 1980, KBS were applied in only a few fields such as medicine and chemistry. During the last decade, there has been a rush to build KBS in a wide range of application areas, including H/WQ modeling (Johnson, 1984; Buchanan, 1986; Plant and Stone, 1991). Davis and Lenat (1982) compiled a bibliography of KBS applications in natural resource modeling. Feher and van Genuchten (1990) developed a KBS to facilitate selection of a particular model as a function of the governing mechanisms and processes, the prevailing soil properties, and the applicable initial and boundary conditions of the physical system simulated. Heatwole (1990) described a knowledge-based interface for improving the usability of the GLEAMS model for resource management. Crowe and Mutch (1992) described a KBS (known as EXPRES) for evaluating the fate of pesticides in the subsurface environment. Lam et al. (1989) described an ES for regional analysis of watershed acidification. In all of these applications, the KBS facilitates: (1) selection of a model from a range of available models that are best suited for the modeling objective, (2) specification of input data required by the model or what compromise (default) data can be used if the preferred data is not available, and (3) analysis and interpretation of modeling results. Because of these benefits, KBS will continue to find widespread application in H/WQ modeling.

Software Engineering: Object-oriented Modeling

Recent initiatives in software engineering, defined generally as the application of traditional engineering principles of planning and design to the production of computer software, have provided grounds for optimism about H/WQ. One such initiative, pioneered for building user interfaces in the Smalltalk™ language (Goldberg and Robson, 1985) and in the area of simulation to support programming in the Simula™ language (Wegner, 1990) is object-oriented programming (OOP). The fundamental concept behind OOP is the logical connection of objects with methods and functions that operate on the object. This connection is achieved through a unique declaration of object classes (Pascoe, 1986). The classes define manipulations and information that will be passed from one module to another. Object-oriented programming attempts to bridge the gap between the physical system whose components may already be well understood and its computer representation of the physical system is structured in a way that minimizes user's need to understand the model (Cox, 1988; Sefik and Bobrow, 1986).

The primary advantage of OOP techniques is that it provides a natural way to divide objects and data (attributes) into individual modules. For example, the model that represents the physical system is created by placing objects that represent the important elements of that system and then connecting them to allow information

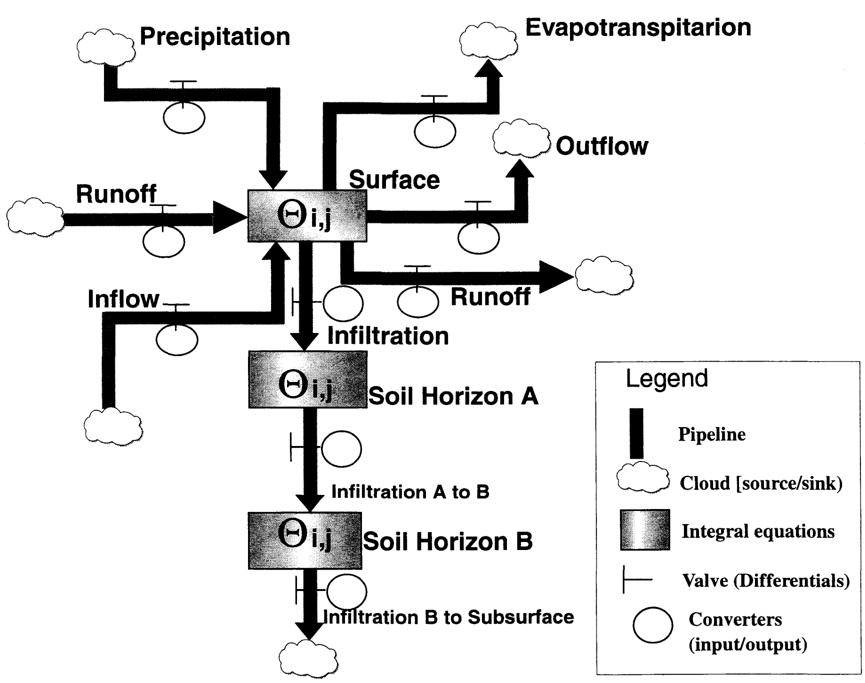

Figure 4–Object-oriented representation of volumetric soil moisture balance.

and operations to be routed (for an example see fig. 4). By so doing, the complicated feedback behavior of the physical system can be analyzed. A properly designed object-oriented modeling environment can reduce model development time, improve software reliability, and enhance the ease-of-use of models. Other benefits include a large measure of independence from specific programming language, data encapsulation, reduced sensitivity to program modification, rapid prototyping and testing of software components, and reuse of basic modeling modules (Mckim et al., 1993; Booch, 1991). Because of these potential benefits, a number of attempts have been made to use them in modeling hydrologic systems. Wolfe and Whittaker (1990) described an object-oriented approach to simulating infiltration and overland flow in watersheds. Objects were represented by hydrologic response units, while the operation associated with each object was based on the Green-Ampt equation (Green and Ampt, 1911). Crosby and Clapham (1990) used an object-oriented approach in Smalltalk™ language to simulate nitrogen dynamics in plants. Sequeira et al. (1991) developed an object-oriented cotton growth model to examine the interaction between localized pest infestations and cotton yield and quality.

Technology for Data Acquisition

Reliable and accurate data are essential if H/WQ models are to benefit from the technological prowess in computer technology. Models and data are inseparable and together provide the basis for improved understanding of hydrologic processes and for documenting the impact of human activities on the environment. Good models illuminate the quality of the data and make it much easier to design experiments to answer specific research questions or pinpoints areas where knowledge is lacking. Good data, on the other hand, permits the development of accurate models, generating or testing of new hypotheses, and extension of models to other areas with limited information. This complimentary relationship between model and data was stressed by Dunne (1982) who noted:

> *The most vigorous and sophisticated current developments in hydrology are due to the efforts of researchers concerned with physically based mathematical models. However, this expanding frontier will be hollow unless it is matched by equally sophisticated field experimentation to discover unexpected hydrologic phenomenon, to develop new concepts about familiar processes, and to guide the development of mathematical models based on sound physical insights into field conditions.*

Recent technological innovations in remote and direct acquisition of data offer unique opportunities for H/WQ modeling. These innovations are in the areas of remote sensing, global positioning systems, and sensors (e.g., noninvasive techniques of resonating high-frequency electromagnetic radiation). Space limitations do not permit an exhaustive treatment of these technologies; therefore, this section will concentrate only on remote sensing and global positioning technologies.

Remote Sensing. Rango (1994) presented a detailed description of the theory and application of the remote sensing technology in hydrology and water resources. Generally, remote sensing involves the inference of properties of the subsurface, surface, and atmosphere from the measurement of reflection or emission of electromagnetic radiation made primarily from satellites and aircraft. The remote sensing technology offers many opportunities for obtaining frequent measurements of hydrologic data over a wide range of spatial and temporal scales. Gradually remote sensing is becoming an essential component of hydrological sciences since it allows examination of interactions of different terrestrial components (Duchon and Nicks, 1990). Because hydrologic processes, for example, modify the electromagnetic signal in some part of the spectrum, important variables can be measured directly by remote sensing instruments. For example, remote measurements of visible, near-infrared, and thermal infrared wavelengths obtained from remote sensors can be used to estimate hydrologic parameters including the presence or absence of vegetation cover, structure of vegetation (e.g., biomass, leaf density), stress in vegetation, moisture content of soils and plant leaves, soil texture, snow cover and its rate of depletion, and soil organic matter.

During the last two decades, the techniques of remote sensing have significantly improved and continue to evolve. New satellites launched in the last few years provide unique opportunities for collection of data at very fine spatial and temporal scales. Landsat with 30 m data resolution and SPOT with 10 m data resolution continue to provide large volumes of data for land cover classifications. The synthetic aperture radar (SAR) on the Japanese Earth Resource Satellite (JERS1), which operates at 1.4 GHZ and penetrates deeper into soil and vegetation, provides better estimates of soil moisture. The European Space Agency's ERS-1 radar satellite and its SAR instrument operates at 6 GHZ and provides reliable data for mapping snow cover. This sensor can penetrate clouds and also acquire data at night. The next-generation weather radar (NEXRAD), operated by NOAA, provides accurate real-time and retrospective precipitation data from ground-based radar. Furthermore, the Canadian RADARSAT to be launched sometime in 1995 into the sun-synchronous orbit will transmit very detailed radar data for environmental management.

Several new initiatives will advance the availability and use of remotely sensed data. Recently, the U.S. government agreed to the commercial sale of image data collected from privately owned satellites with spatial resolution as fine as 1 M. With data being declassified at unprecedented rates, there is possibility of using relatively recent high-resolution data to assist environmental modeling efforts. Also with the move towards information super-highways, the use of satellite data will be absolutely essential. Several other direct sensing systems will contribute to data acquisition. For example, research frontiers in subsurface remote sensing, particularly the techniques of ground penetrating radar and tomographic reconstruction (similar to the Cat-Scan equipment used in medical research) will provide characterization of subsurface hydrologic properties such as hydraulic conductivity and the spatial extent of contaminant plumes. Other techniques such as dielectric probes and time-domain reflectrometry will contribute significantly to the collection of soil moisture data.

Global Positioning Systems. An essential requirement for direct sensing of spatially variable input parameters (e.g., soil moisture content, hydraulic conductivity, etc.) for H/WQ modeling is a means to accurately locate the data-collection points within the landscape (plot, field, watershed). Various techniques to determine the precise location of sampling points within a field have been described in the literature. However, the most widely used system for position fixing is provided by global positioning systems or GPS. The GPS technology allows accurate locations of points on the earth's surface on the basis of a constellation of satellites placed in orbit by the U.S. Department of Defense. Each satellite, which transmits a composite signal that may be picked up by a microwave receiver, has an atomic clock to precisely time the signal codes (e.g., coarse acquisition code or C/A code and precise positioning service code or P code). A GPS receiver generates a duplicate of the code sequence and the time shifts to correlate with received code sequence (Kruger et al., 1994). Thus, the time delay between transmission and reception of signals can be determined. From this time delay, the range to each satellite can be calculated by reference to the velocity of propagation of electromagnetic radiation. Provided that the receiver has line-of-sight to sufficient satellites, the position of the receiver can be determined either by measuring the time delay (pseudo-ranges) between transmission and reception of signal or by the phase-shift measurement of the signal carrier. Reception of at least four satellite signals is required to determine the three-dimensional position of the receiver. The measured three-dimensional coordinates of the point of interest are available in the spatially fixed Cartesian coordinate system. These coordinates can be converted into longitude, latitude, and altitude coordinates.

Barring any new complications in selective availability code from the U.S. Department of Defense, the GPS technology will likely continue to be used for civilian applications. Currently, applications of the GPS technology in H/WQ have been limited to site-specific farming (e.g., site-specific chemical treatment for insect and weed control, application of irrigation water and fertilizer, etc.) and management of environmental pollution (Environmental Protection Agency, 1992). However, future applications of GPS will probably include accurate location of soil and water quality data sampling points, which could be post-processed as location inputs to H/WQ models; location of chemical application areas; and detailed study of the effects of spatial variability on modeling results. With the cost of GPS receivers dropping dramatically, the H/WQ modeling community is beginning to incorporate site-specific data into models. The successful adoption of the GPS technology in data acquisition for H/WQ modeling will depend largely on the availability of signals as well as the technological advancement in GPS receivers.

Summary and Conclusions

Over the past several decades, the art of H/WQ modeling research has expanded rapidly as a result of the dramatic increases in the performance of computers coupled with an improved understanding of the processes that govern the flow of fluids and pollutants in the terrestrial environment. During this period, new methodological approaches to H/WQ modeling have emerged, and numerous research programs in modeling have been initiated worldwide. These research initiatives have yielded a plethora of models that provide the framework for piecing together components of complex systems in a unified manner to create a theoretical construct of the total physical system.

Since the pioneering efforts of researchers such as Horton, Saint Venant, and Chow, among many others, the art of H/WQ modeling has developed rapidly and currently has a diverse user community with very different interests. Although the capabilities of existing H/WQ models have improved during the past decades, users' expectations continue to rise. The capabilities of H/WQ model must therefore continue to develop to meet these expectations. In spite of the increasing difficulty in improving the capabilities of H/WQ models, recent and emerging technological advancements in computer hardware and software hold great promise. This article examined some of these emerging technologies that are bound to improve the capability and applicability of H/WQ models. The emerging technologies examined in the article include user interfaces, virtual reality, animation, remote sensing, GIS, KBS, GPS, and OOP.

Since H/WQ modeling research in the past has closely paralleled the developments in computer technology, future modeling efforts will need to incorporate some of the emerging technologies discussed in this article. Other challenging research issues in H/WQ modeling that need more effort include resolving scale problems in models, improving data collection, developing comprehensive decision support systems that incorporate most or all of the technologies discussed in this article, and developing an efficient approach to characterizing parameter uncertainty in models. In addition, adequate procedures to test, calibrate, and validate H/WQ models remain an important research issue.

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